Theories of Quantum Gravity

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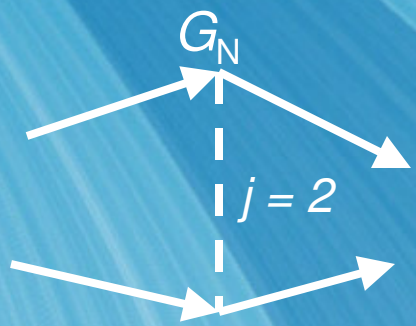
QG: Why should we care?

- General Relativity has a well-known prescription for quantization; but it is badly behaving.
- Black Holes obey 'thermodynamics', but related to Area, not Volume!
- Big Bang seems to be black hole collapse, run in reverse!
- Expect equivalent results from high accelerations; soon possible in the lab.
- Quantizing spacetime affects propagation of very high energy photons: TeV range.

Side Trip: QFT

- Perturbation theory solves the problem of the self-energy of the electron.
- Point-like interactions are difficult to cure:
  - Energy increases with smaller distances.
  - Regularization 'smears' out the interaction.
- Naïve Quantum Gravity is not cured by perturbation theory.

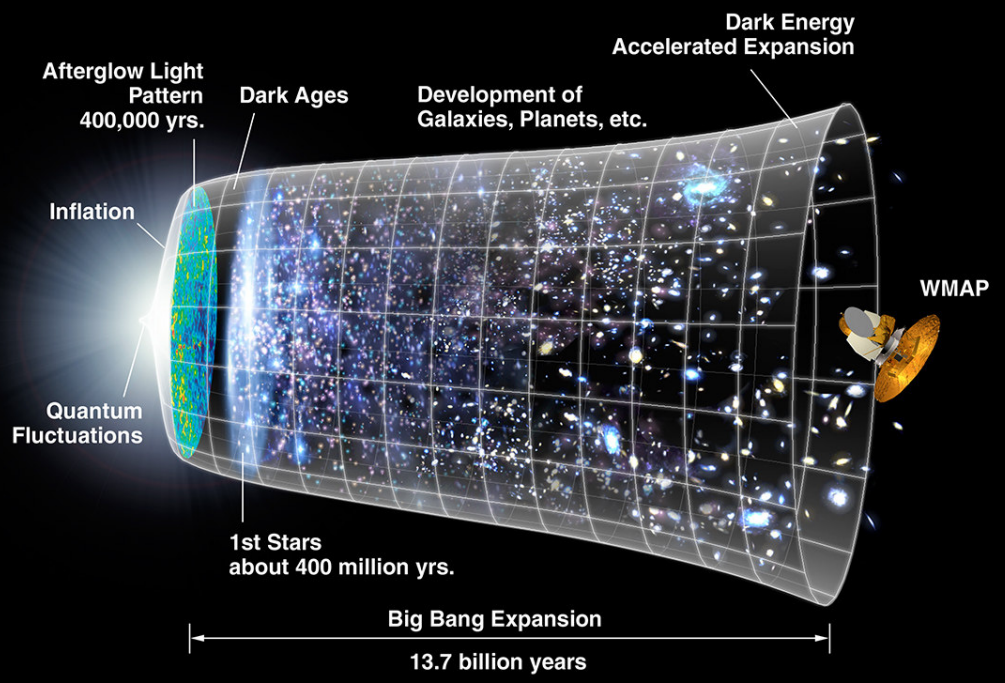
$$M \sim 1 - \lambda + \lambda^2 \ln(E/E_0) - \ldots$$



$$M \sim 1 + G_N E^2 + (G_N E^2)^2 + \ldots$$

White Hole Origin of the Universe

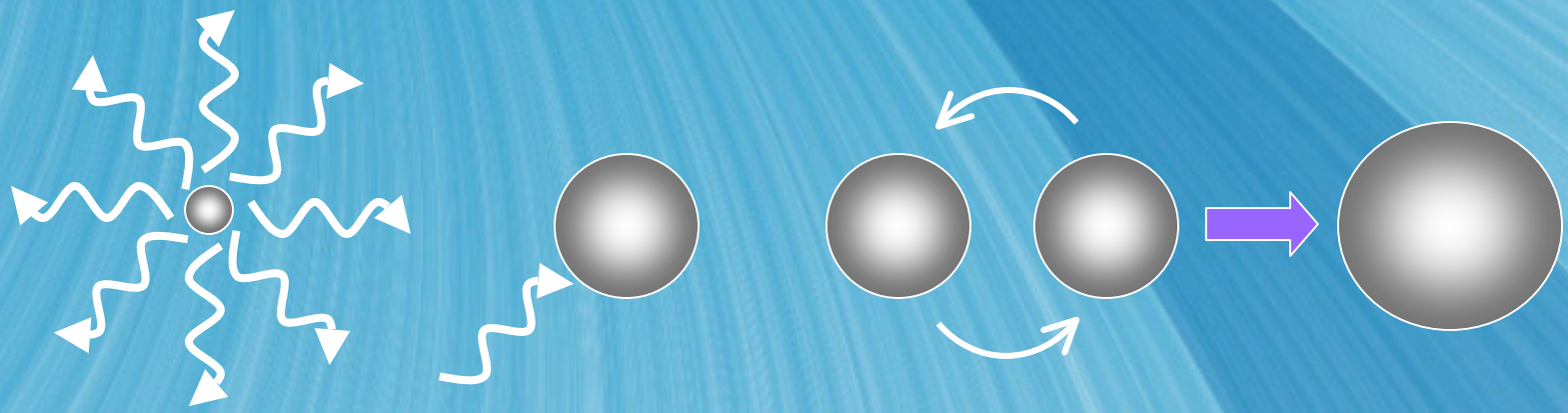
Run time backwards (Penrose) …
… looks like collapse to BH!



At the center of BH is a singularity; physics is broken.
Why should this particular BH be any different?

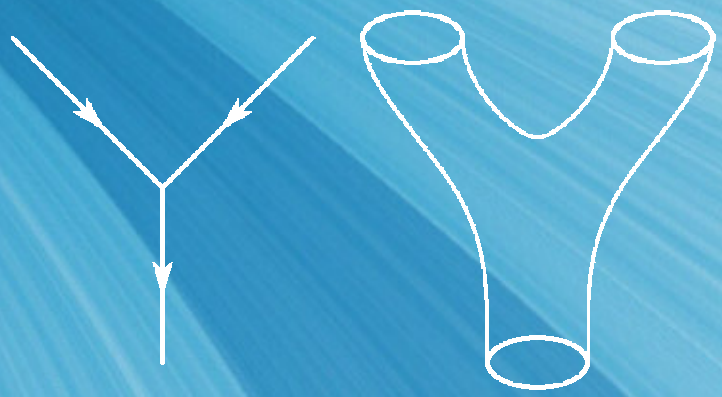
Black Hole Thermodynamics

- Hawking's famous three laws for BH area:
  - Zeroth Law: BHs have a temperature: $S = 1/4\ A\ /\ h_{bar} G_N$
    or: $T = h_{bar}\, c^3 /(16\ \pi^2\ k_b\ G_N\ M) \sim (6 \times 10^{-8}/M)\ K$.
  - First Law: Total energy (=area) of BH is always conserved.
  - Second Law: $\sum A_{before} < \sum A_{after}$ or $\Delta A > 0$.



Solution 1: String Theory

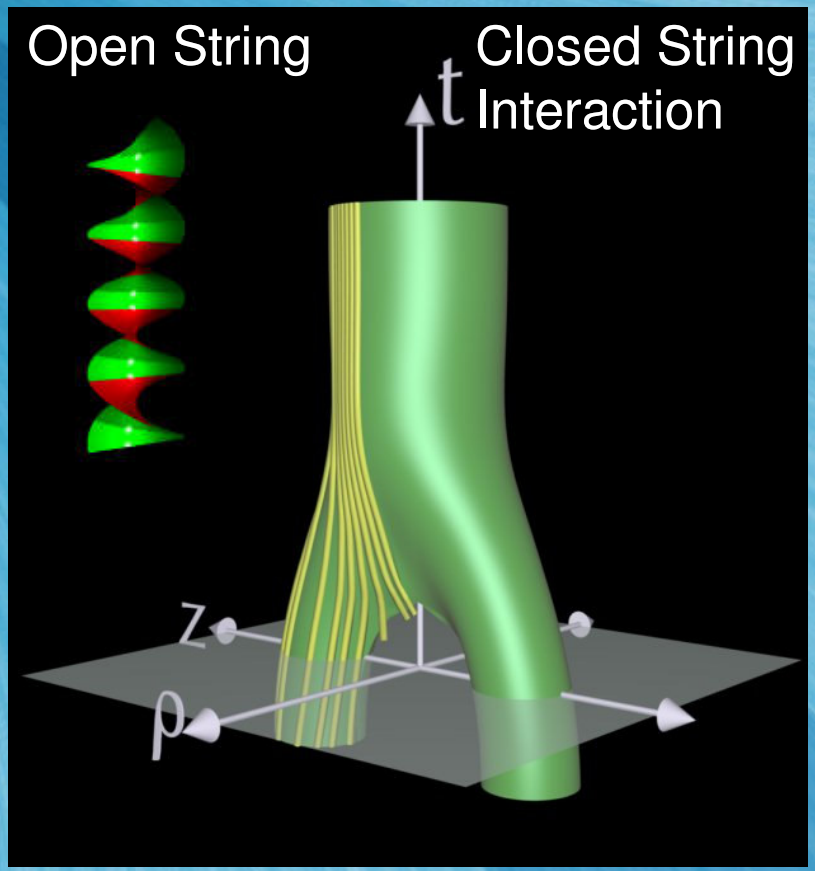
- Elegant solution to non-renormalization of QG.
- Gravity is a 'natural' consequence of local SUSY.
- Links high-energy particle physics with gravity.
- Supportive of 'chaotic inflation' theory for the early universe.
- Gives a 'solution' to BH thermodynamics.



Point particle & Closed String

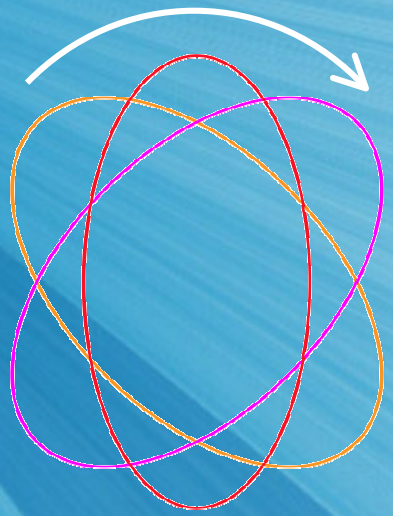
What are Strings?

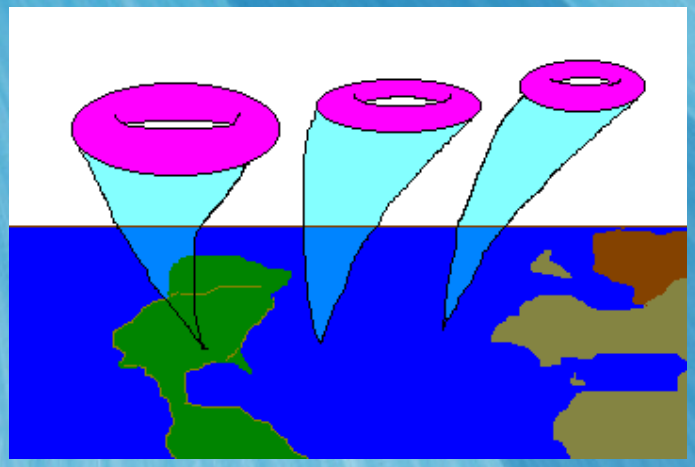
- Extended 1D objects with 1 property: tension.
- Motion of 1D object in time: 2D sheet.
  - Bosons: closed loop
  - Fermion: open string
- Interactions are non-local: no divergences!
- Massive particles are generated by vibrational modes.



Anomalies & Extra Dimensions

- Consider the number of dimensions strings occupy:
  - 2D: Intrinsic geometry of the string
  - 4D: observable universe
  - 10D or 32D: required for consistency of the Quantum theory (no anomalies)
- Extra dimensions are 'OK', if they are not observable:
  - Kaluza-Klein: rolled up
  - Global vs. Local gauge





SuperSymmetry (SUSY)

- Converts bosons (j = 1, 2) into fermions (j = 1/2) & v.v.
- Ingredient of 10D string theory:
  - Uniqueness: 4 models (interchangeable!)
  - Local SUSY generates gravity automatically!
  - QG is free of divergences (#f = #b).
- SUSY is not observed at all (too restrictive)!

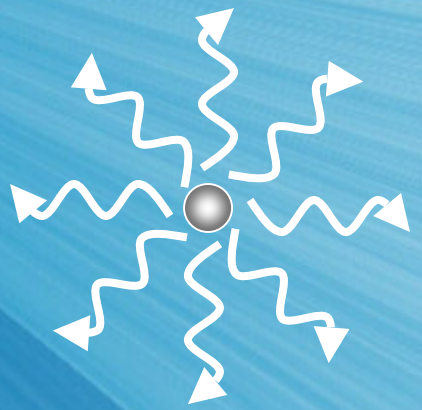
Fundamental Force Particles

Force	Particles Experiencing	Force Carrier Particle	Range	Relative Strength*
Gravity acts between objects with mass	all particles with mass	graviton (not yet observed)	infinity	much weaker
Weak Force governs particle decay	quarks and leptons	W^+, W^-, Z^0 (W and Z)	short range	
Electromagnetism acts between electrically charged particles	electrically charged	γ (photon)	infinity	
Strong Force** binds quarks together	quarks and gluons	g (gluon)	short range	much stronger

- Gravitino (j = 3/2)
- Winos, Zinos, Photinos, Gluinos (j = 1/2)
- Squarks, Sleptons (j = 0)

Stringy Successes and Failures

- Black Hole temperature (Polchinski):
  - Start with extremal BH ($a = 1$)
  - Replace with string equivalent (using branes - don't ask!)
  - Count up microcanonical states
  - Entropy gives $T = 1/(8\, k_b\, M)$!



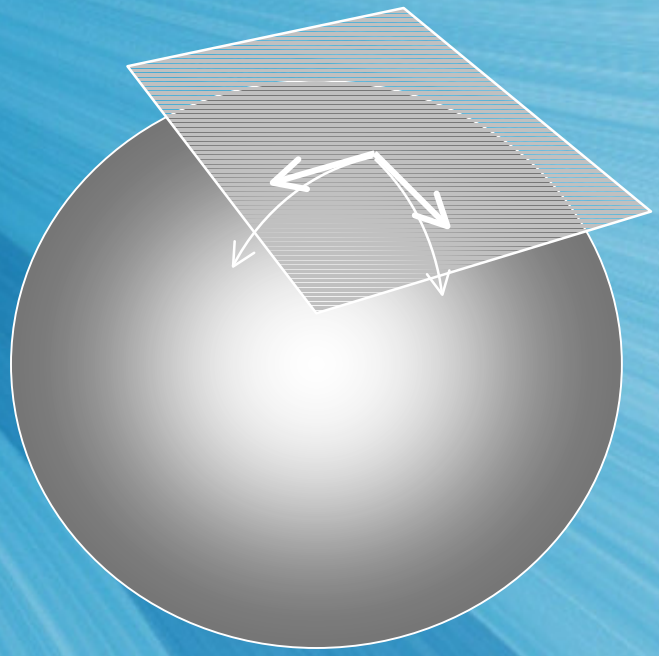
- Supergravity is <u>not</u> classical gravity: strings, like particles in QFT, move on a background spacetime.
- No unique way to collapse down from 10 to 4 dimensions (however: all compactifications are related)

Solution 2: Loop QG

- LQG is based upon the following ingredients:
  - Quantum Mechanics + General Relativity.
  - Background geometry independence.
  - No unification of forces.
  - Four spacetime dimensions and no SUSY.
- The 'loops' in LQG are like Faraday 'lines of force'. Their connectivity is what's important, not their position.
- Gravity is a field, same as QFT of particles and other forces (QED, QCD, & Weak). It generates space & time, not propagate in it.

Vierbein Formalism

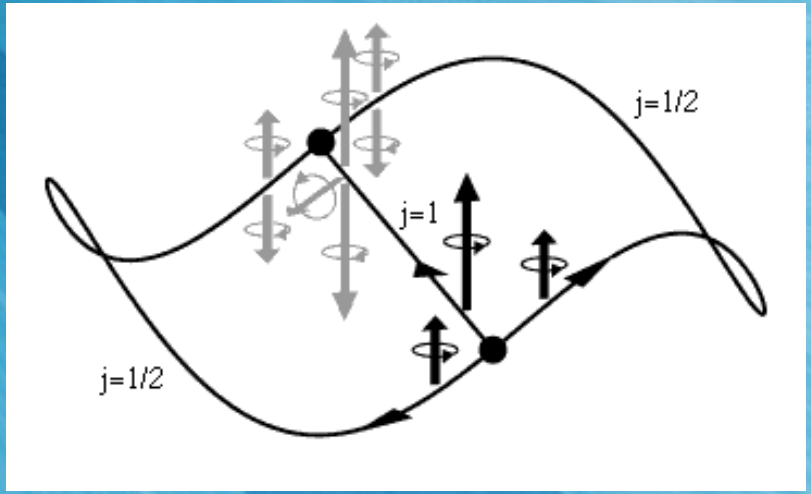
- The spacetime metric $g_{\mu\nu}$ has a 'square root':
  $g_{\mu\nu} = e_\mu^{\ a}\, e_\nu^{\ b} \eta_{ab}$
- Einstein's GR can be rewritten in terms of this 'vierbein' (= '4 legs'):
- Write $e^a = e_\mu^{\ a}\, dx^\mu$, then $de^a = -\omega^{ab} e^b$ defines the 'spin connection' and $R^{ab} = d\omega^{ab} + \omega^{ac}\,\omega^{cb}$ = the curvature.
- Relates 'curved' (spacetime) coords with 'flat' (tangent) coords.



- $ds^2 = d\theta^2 + \sin^2\theta\, d\phi^2$
- $e_\theta^{\ 1} = 1 \qquad e_\phi^{\ 2} = \sin\theta$
- $e^1 = d\theta \qquad e^2 = \sin\theta\, d\phi$
- $-\omega^{12} = \omega^{21} = \cos\theta\, d\phi$
- $R^{12} = \sin\theta\, d\theta\, d\phi;\ R=4\pi$

Vierbein to Spin Foam

- Rewrite vierbeins as ‘spin connections’ and the Lagrangian *R* as a Hamiltonian & solve.
- Unique solution is spin network: graphs with edges labeled by spins: ‘loops’.
- Codifies what we think of as ‘curvature’:

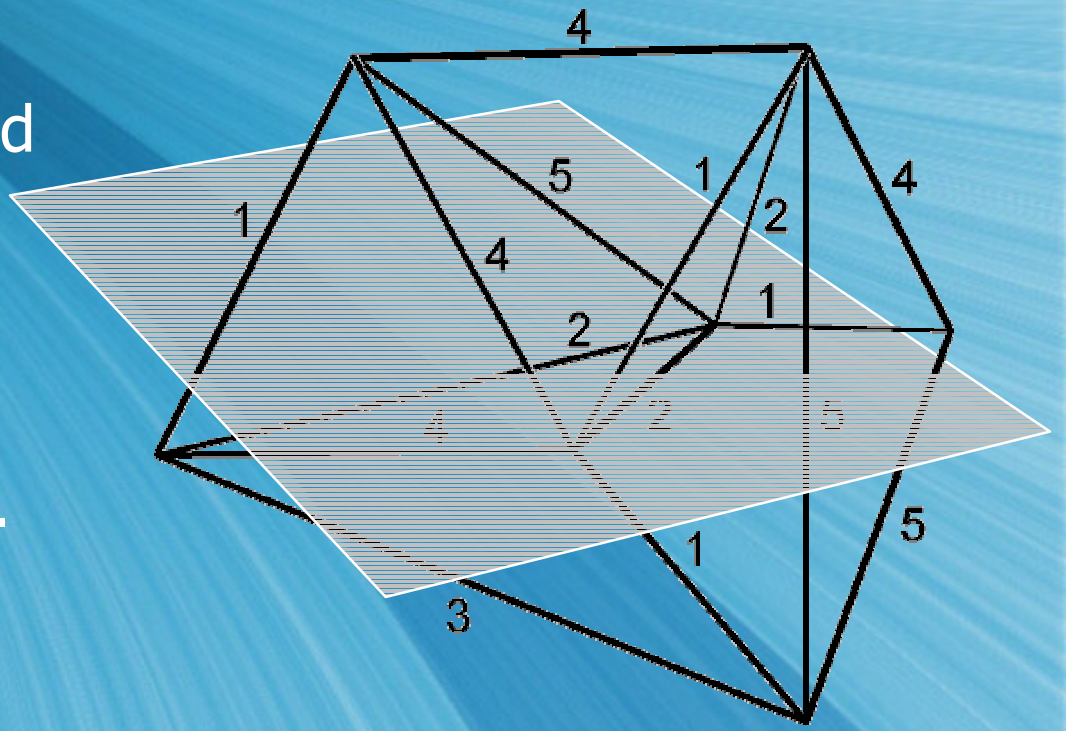


Parallel transport around a loop will produce a vector that is rotated compared to its original orientation; with curvature the sum of angles of a triangle being different from 180.

Spin Foam to Quantized Area

- Take any 2D plane and cut spin network.
- Each edge represents one quantum of Area!
- ↙Spins=deficit angle over plane=curvature.
- In particular: BH area gives:

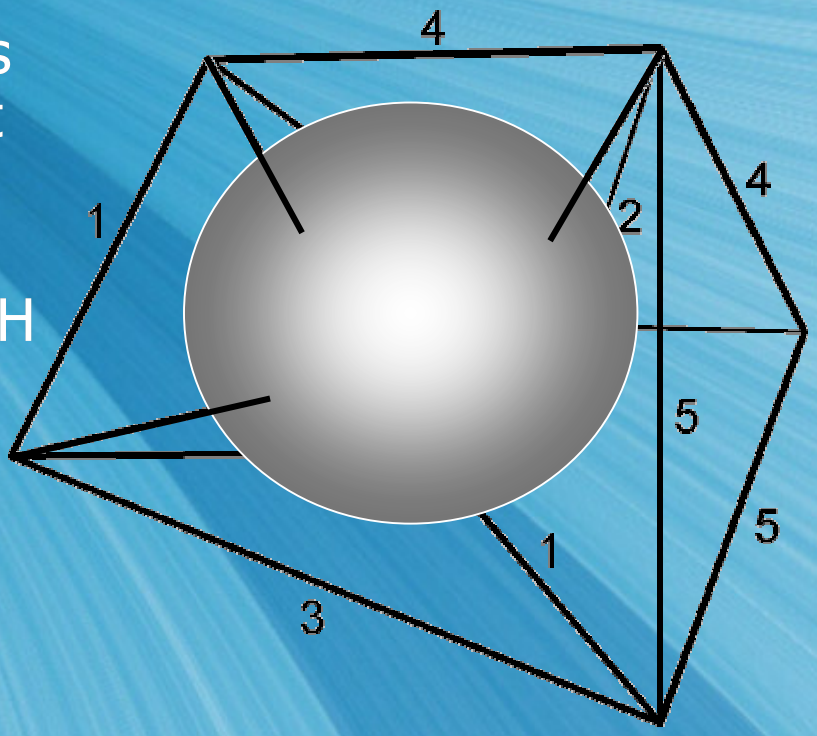
  S=γ 1/4 A / h_{bar} G_N
- Immirzi parameter γ is not constrained; = 1 (1D family of solutions).



$$A_\Sigma = 8\pi G_{\text{Newton}} \gamma \sum_i \sqrt{j_i(j_i+1)}$$

Holographic Principle

- One problem with classical BHs is that information goes in, but can never come out: *V>>A.*
- Spin network intersects the BH horizon: only the area of the BH is important.
- Area is quantized: 1/4 bit per unit area can pass through to observer.
- Holographic Principle: information is limited by the surface it passes through.
- BH as blackbody!



LQG Successes & Problems

- Succeeds in quantizing area (& volume; but this is definition-dependent!).
- Spin network looks 'smooth' at large scales.
- BH temperature has only one free parameter.
- Vierbein theory is at least *renormalizable*.
- Very little guidance for particle physics; unlike with strings.
- Not *really* covariant: 3+1 formalism.

Explorations and Suggestions

- There are many other approaches in the literature; this one's mine (but it seems to be related to gravitometrodynamics).
- Make use of some of the best elements from each of the two other approaches.
- Not at the level of an actual theory (yet!).

How Many Dimensions?

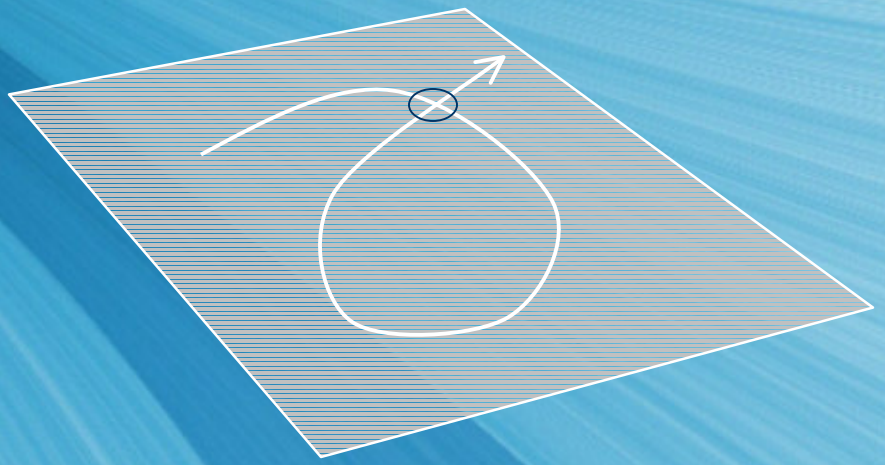
- The 4D metric $g_{\mu\nu}$ is a symmetric 4X4 tensor = 10D required (Feynman)
- Whitney's Embedding Theorem says:

2 X 4D = 8D is necessary;

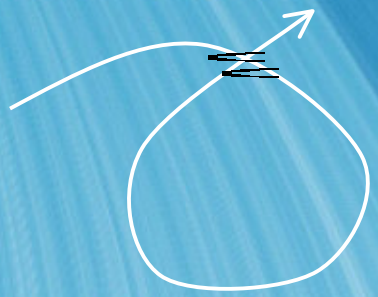
2 X 4D + 1 = 9 is sufficient.

- The 'extra' 1D is to avoid self-intersections (think Klein bottle).
- Self-intersections in Spacetime are bad.

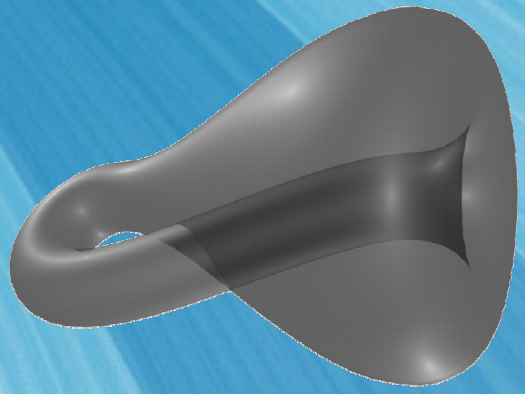
2 X 1D = 2D



2 X 1D + 1 = 3D



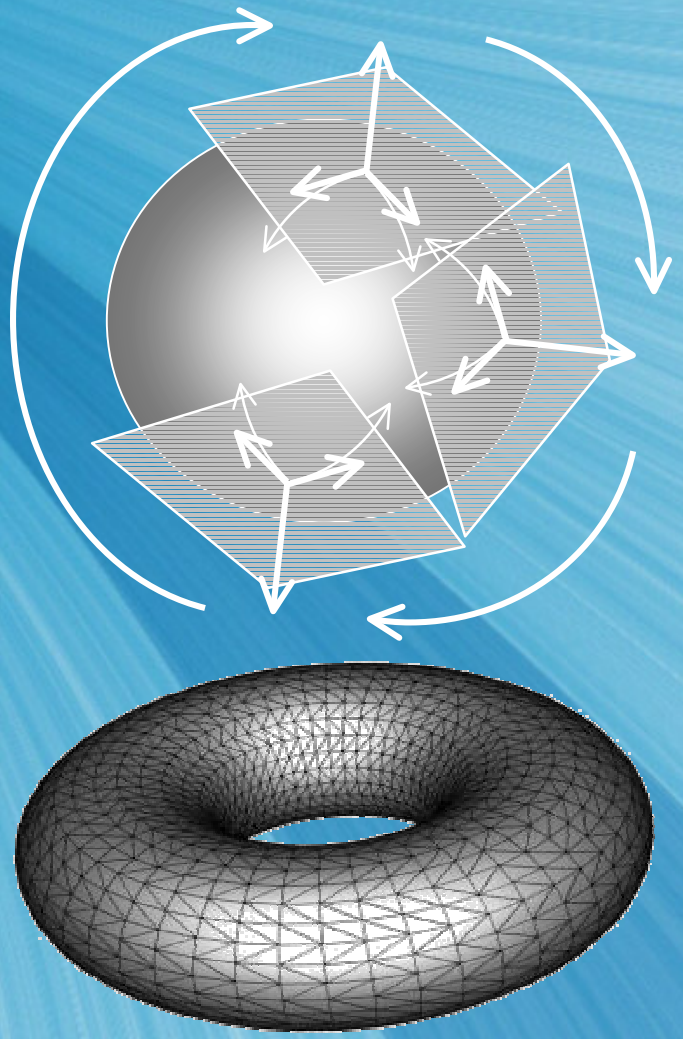
2 X 2D + 1 = 5D



Vier (4) to Viel ('many')

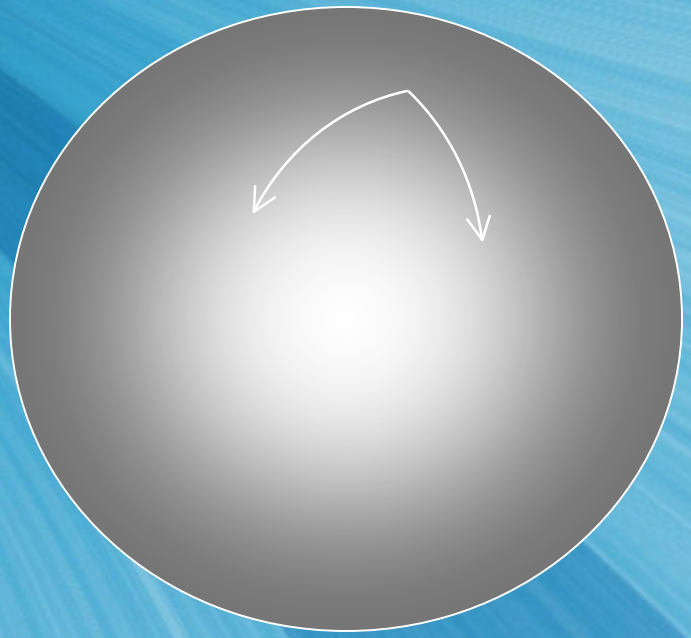
- Adding extra dimensions to Vierbein embeds spacetime in 8 (or 9) dimensions.
- Normal 'legs' allow us to define the ST topology: 'class of shape'.
- Lagrangian of Vielbein is topological:

  $R = d\omega + \omega^2$
- Quantize shape: the more knots, the higher the energy.



Extra Legs: More Symmetry

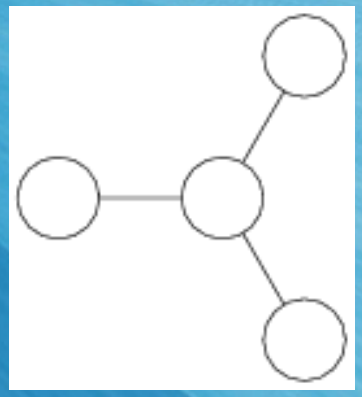
- In 4D, the vector just 'happens' to also represent the spinor (electron: j=1/2)
- SUSY works by expanding available symmetries; doubling degrees of freedom.
- We could do better: choose a symmetry that has more than one representation for the same dimension.



$SU(2) \cong SO(3)$

SO(8): The Perfect Symmetry

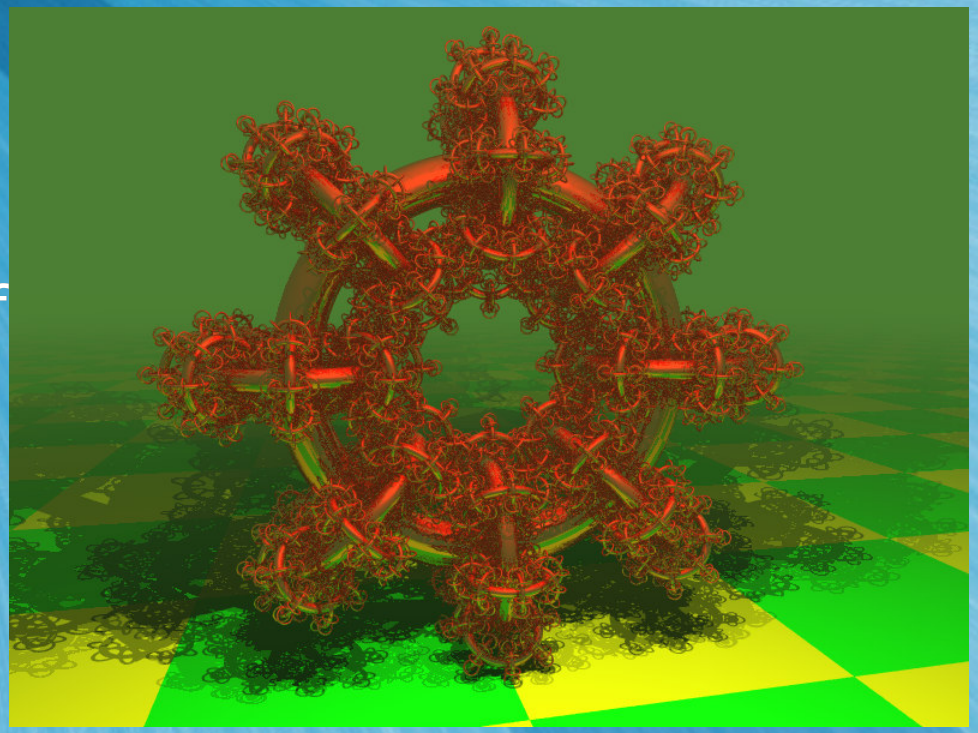
- Start with 9D Euclidean reference space.
- Take 8D as spatial.
- Lorentz symmetry group is naturally *SO(8).*
- Look for particle representations within *SO(8).*
- Identify the *Vector* with 8D *Spin*: equal numbers!
- Get SUSY-like cancellations between Fermions & Bosons.



- SO(8) is unique among the simple Lie groups in that its Dynkin diagram possesses a three-fold symmetry.
- The two spinor representations, as well as the vector representation, of Spin(8) are all 8D (for all other spin groups this is either smaller or larger than the vector representation).

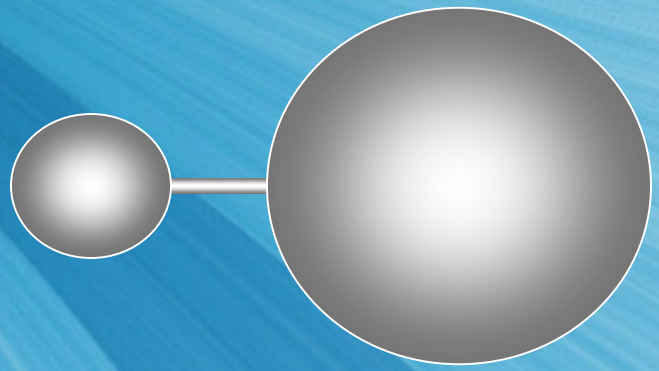
Strong-Field Gravity

- At high field strength: small curvature. Higher energy: higher 'knottedness' (genus).
- Propose 'Pauli principle' for knots: no two knots of same genus can occupy the same region.
- Degeneracy of Spacetime topology 'smears' BH singularity: no divergences below Planck length scale.
- All field theories are finite!



Cosmological Inflation

- Today, we see 4 dimensions, not 8 or 9!
- In the early universe, 4 out of 8 spatial dimensions gain energy (curvature) and 4 lose energy (inflation).
- Generates free energy for the expansion of the primordial Universe.
- Prediction: spectrum of primordial knots (if you could calculate it!) = spectrum of CMB.

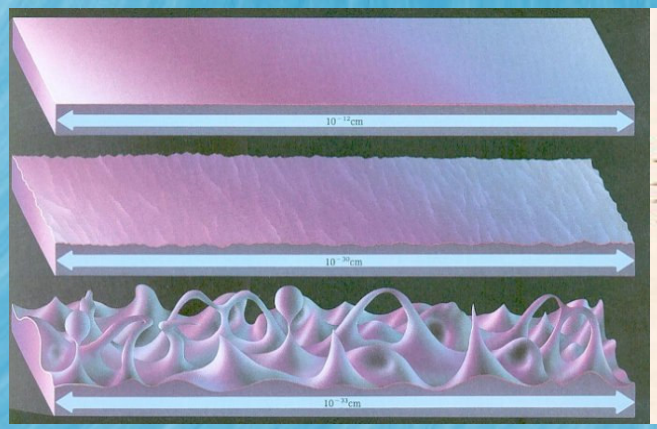


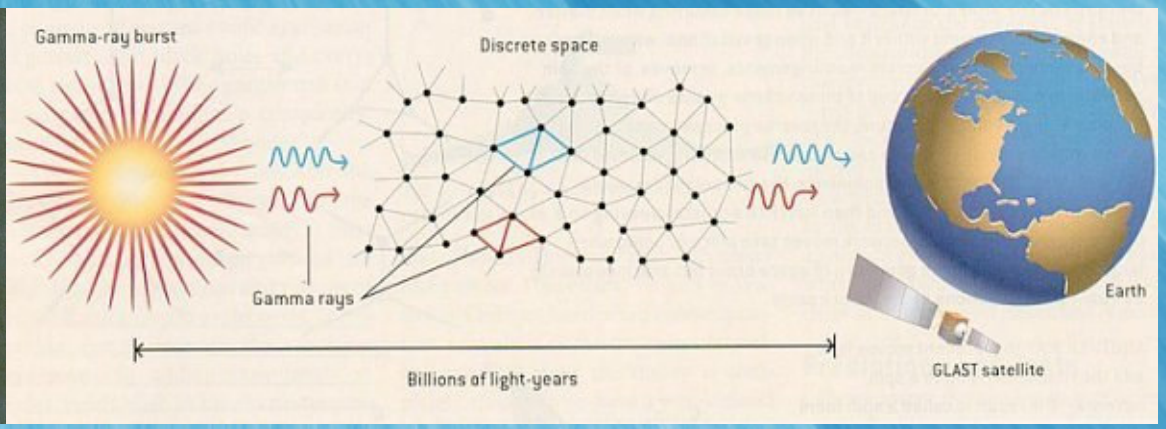
Two balloons with identical properties are connected by a pipe.

Does the smaller balloon get larger or smaller?

GLAST and QG

- Higher energies probe smaller features.
- Spacetime becomes corrugated, photon travels 'farther':
  - Either trace ST knots or discrete lattice of quantized area, or ...
- Must assume a particular relation between energy and time within a GRB:
  - A relation has already been observed: spectral lag is somewhat correlated with luminousity - Norris, et al.
  - Chance coincidence: bright, close, very hard GRB with very sharp leading edge pulse - and TeV observation by ground array





Wrapping up:

- QG has not been solved yet; strings, LQG, etc., each have something to contribute.
- BH singularity is largely solved by 'quantum degeneracy of spacetime'; relevant also to Big Bang.
- With some progress, observable predictions could be given.
- Don't even *ask* about branes…